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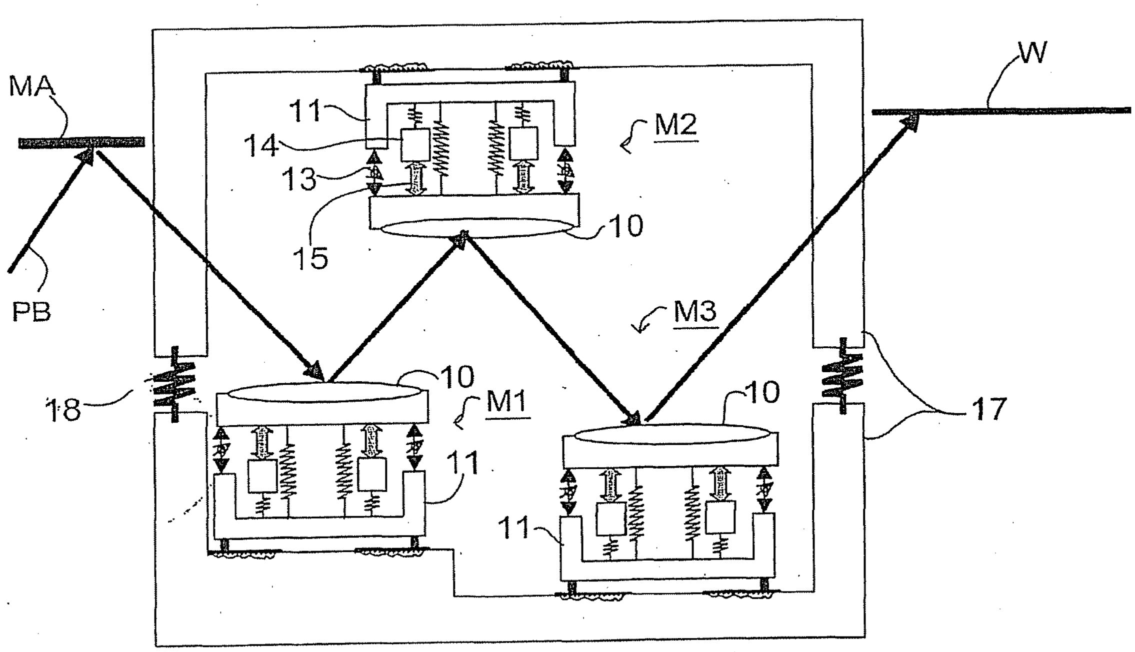
(54) Lithographic apparatus and device manufacturing method

(57) A reaction mass 14; 54; 64 and an actuator 15; 55; 65 are used to reduce unwanted vibrations of an optical element 10; 50; 60 in the projection system of a lithographic projection apparatus. The reaction mass 14; 54; 64 may be mechanically connected only to the optical element 50; 60 or may be compliantly mounted to the projection system frame 11.

Fig. 2



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Description

[0001] The present invention relates to a lithographic projection apparatus comprising:

- a radiation system for supplying a projection beam of radiation;
- a support structure for supporting patterning means, the patterning means serving to pattern the projection beam according to a desired pattern;
- a substrate table for holding a substrate; and
- a projection system for projecting the patterned beam onto a target portion of the substrate.

[0002] The term "patterning means" as here employed should be broadly interpreted as referring to means that can be used to endow an incoming radiation beam with a patterned cross-section, corresponding to a pattern that is to be created in a target portion of the substrate; the term "light valve" can also be used in this context. Generally, the said pattern will correspond to a particular functional layer in a device being created in the target portion, such as an integrated circuit or other device (see below). Examples of such patterning means include:

- A mask. The concept of a mask is well known in lithography, and it includes mask types such as binary, alternating phase-shift, and attenuated phase-shift, as well as various hybrid mask types. Placement of such a mask in the radiation beam causes selective transmission (in the case of a transmissive mask) or reflection (in the case of a reflective mask) of the radiation impinging on the mask, according to the pattern on the mask. In the case of a mask, the support structure will generally be a mask table, which ensures that the mask can be held at a desired position in the incoming radiation beam, and that it can be moved relative to the beam if so desired.
- A programmable mirror array. One example of such a device is a matrix-addressable surface having a visco-elastic control layer and a reflective surface. The basic principle behind such an apparatus is that (for example) addressed areas of the reflective surface reflect incident light as diffracted light, whereas unaddressed areas reflect incident light as undiffracted light. Using an appropriate filter, the said undiffracted light can be filtered out of the reflected beam, leaving only the diffracted light behind; in this manner, the beam becomes patterned according to the addressing pattern of the matrix-addressable surface. An alternative embodiment of a programmable mirror array employs a matrix arrangement of tiny mirrors, each of which can be individually tilted about an axis by applying a suitable localized electric field, or by employing piezoelectric actuation means. Once again, the mirrors are matrix-addressable, such that addressed mirrors will reflect an incoming radiation beam in a different direction to unaddressed mirrors; in this manner, the reflected beam is patterned according to the addressing pattern of the matrix-addressable mirrors. The required matrix addressing can be performed using suitable electronic means. In both of the situations described hereabove, the patterning means can comprise one or more programmable mirror arrays. More information on mirror arrays as here referred to can be gleaned, for example, from United States Patents US 5,296,891 and US 5,523,193, and PCT patent applications WO 98/38597 and WO 98/33096, which are incorporated herein by reference. In the case of a programmable mirror array, the said support structure may be embodied as a frame or table, for example, which may be fixed or movable as required.
- A programmable LCD array. An example of such a construction is given in United States Patent US 5,229,872, which is incorporated herein by reference. As above, the support structure in this case may be embodied as a frame or table, for example, which may be fixed or movable as required.

For purposes of simplicity, the rest of this text may, at certain locations, specifically direct itself to examples involving a mask and mask table; however, the general principles discussed in such instances should be seen in the broader context of the patterning means as hereabove set forth.

[0003] Lithographic projection apparatus can be used, for example, in the manufacture of integrated circuits (ICs). In such a case, the patterning means may generate a circuit pattern corresponding to an individual layer of the IC, and this pattern can be imaged onto a target portion (e.g. comprising one or more dies) on a substrate (silicon wafer) that has been coated with a layer of radiation-sensitive material (resist). In general, a single wafer will contain a whole network of adjacent target portions that are successively irradiated via the projection system, one at a time. In current apparatus, employing patterning by a mask on a mask table, a distinction can be made between two different types of machine. In one type of lithographic projection apparatus, each target portion is irradiated by exposing the entire mask pattern onto the target portion in one go; such an apparatus is commonly referred to as a wafer stepper. In an alternative apparatus —commonly referred to as a step-and-scan apparatus — each target portion is irradiated by progressively scanning the mask pattern under the projection beam in a given reference direction (the "scanning" direction) while synchronously scanning the substrate table parallel or anti-parallel to this direction; since, in general, the projection system will have a magnification factor M (generally < 1), the speed V at which the substrate table is scanned will be a factor M times that at which the mask table is scanned. More in-

formation with regard to lithographic devices as here described can be gleaned, for example, from US 6,046,792, incorporated herein by reference.

[0004] In a manufacturing process using a lithographic projection apparatus, a pattern (*e.g.* in a mask) is imaged onto a substrate that is at least partially covered by a layer of radiation-sensitive material (resist). Prior to this imaging step, the substrate may undergo various procedures, such as priming, resist coating and a soft bake. After exposure, the substrate may be subjected to other procedures, such as a post-exposure bake (PEB), development, a hard bake and measurement/inspection of the imaged features. This array of procedures is used as a basis to pattern an individual layer of a device, *e.g.* an IC. Such a patterned layer may then undergo various processes such as etching, ion-implantation (doping), metallization, oxidation, chemo-mechanical polishing, etc., all intended to finish off an individual layer. If several layers are required, then the whole procedure, or a variant thereof, will have to be repeated for each new layer. Eventually, an array of devices will be present on the substrate (wafer). These devices are then separated from one another by a technique such as dicing or sawing, whence the individual devices can be mounted on a carrier, connected to pins, etc. Further information regarding such processes can be obtained, for example, from the book "Microchip Fabrication: A Practical Guide to Semiconductor Processing", Third Edition, by Peter van Zant, McGraw Hill Publishing Co., 1997, ISBN 0-07-067250-4, incorporated herein by reference.

[0005] The lithographic apparatus may be of a type having two or more substrate tables (and/or two or more mask tables). In such "multiple stage" devices the additional tables may be used in parallel, or preparatory steps may be carried out on one or more tables while one or more other tables are being used for exposures. Dual stage lithographic apparatus are described, for example, in US 5,969,441 and WO 98/40791, incorporated herein by reference.

[0006] For the sake of simplicity, the projection system may hereinafter be referred to as the "lens"; however, this term should be broadly interpreted as encompassing various types of projection system, including refractive optics, reflective optics, and catadioptric systems, for example. The radiation system may also include elements operating according to any of these design types for directing, shaping or controlling the projection beam of radiation, and such elements may also be referred to below, collectively or singularly, as a "lens" or as a "projection system element". The projection system of a lithographic apparatus such as that described above must project the patterned beam onto the target portion of the substrate with very high accuracy and without introducing errors such as optical aberration or displacement errors, for example, into the projected image. Refractive and/or reflective elements within the projection system may need to be accurately positioned in one or more (up to six) degrees of freedom per optical element (which may include, for example, linear displacement along three orthogonal axes and rotational displacement around the three axes). A projection system comprising reflective optics is, for instance, disclosed in US 5,815,310 and US 5,956,192 of Williamson, both incorporated herein by reference.

[0007] The accuracy of the positioning of such projection system elements may be affected by vibrations and other positional noise within the projection system and the projection system frame. The positional noise may, for example, be created by influences external to the projection system (such as acoustic noise, residual floor vibrations and scan reaction forces transmitted via the vibration isolation or suspension system between the base frame and the projection optics system) and by internal influences such as the reaction forces of the actuators used to adjust the position of the projection system elements. The optical elements may be mounted directly to a common frame of the projection system or may be mounted on a sub-frame that is mounted to the common frame. Further, the above considerations may also apply to the radiation system and optical elements mounted therein.

[0008] It is an object of the present invention to provide a means of reducing the effect of any disturbing forces and/or displacements within the projection or radiation system on the respective projection or radiation system elements mounted therein.

[0009] This and other objects are achieved according to the invention in a lithographic apparatus as specified in the opening paragraph, characterized in that at least one of said projection and radiation systems comprises at least one optical element connected by an actuator to a reaction mass that is moveable in at least one degree of freedom, the force exerted by the actuator between the reaction mass and the optical element being used to control the position of the optical element in one or more degrees of freedom.

[0010] The present invention can thereby provide a means for enabling sub-nanometer position control of the (transmissive, and reflective) optical elements in the optical (projection or radiation) system. This is done by a position control of one or more (up to six) degrees of freedom of the relative position of the optical element to the frame of the optical system. The greatly improved positional accuracy for the optical elements in the projection system or radiation system provides a corresponding improvement in imaging quality.

[0011] In a preferred embodiment of this aspect of the present invention, the reaction mass is compliantly mounted to a frame of the apparatus, such as a frame of the projection system, and the reaction to the force exerted by the actuator between the reaction mass and the optical element is used to move the optical element to the required position. This can prevent transmission of vibrations caused by the actuator when adjusting the position of the optical element to the remainder of the

apparatus and thence to other optical elements. In addition it can prevent vibrations in the projection system or the radiation system, for example vibrations caused by sources external to the projection or radiation system from being transferred to the optical element.

[0012] In a further preferred embodiment of this aspect of the present invention, the reaction mass is connected only to the optical element and an accelerometer is used to detect the movement of the optical element. Using data from the accelerometer, the reaction to the force exerted by the actuator between the reaction mass and the optical element can be used to reduce the movement of the optical element. This is advantageous as it can reduce any residual vibration in the optical element.

[0013] According to a further aspect of the invention there is provided a device manufacturing method comprising the steps of:

- providing a substrate that is at least partially covered by a layer of radiation-sensitive material;
- providing a projection beam of radiation using a radiation system;
- using patterning means to endow the projection beam with a pattern in its cross-section;
- projecting the patterned beam of radiation onto a target portion of the layer of radiation-sensitive material using a projection system,

characterized in that:

- an actuator is connected between a reaction mass that is moveable in at least one degree of freedom and an optical element in at least one of the projection and radiation systems; and by the step of
- using the force exerted by the actuator between the reaction mass and the optical element to control the position of the optical element.

[0014] Although specific reference may be made in this text to the use of the apparatus according to the invention in the manufacture of ICs, it should be explicitly understood that such an apparatus has many other possible applications. For example, it may be employed in the manufacture of integrated optical systems, guidance and detection patterns for magnetic domain memories, liquid-crystal display panels, thin-film magnetic heads, etc. The skilled artisan will appreciate that, in the context of such alternative applications, any use of the terms "reticle", "wafer" or "die" in this text should be considered as being replaced by the more general terms "mask", "substrate" and "target portion", respectively.

[0015] In the present document, the terms "radiation" and "beam" are used to encompass all types of electromagnetic radiation, including ultraviolet radiation (*e.g.* with a wavelength of 365, 248, 193, 157 or 126 nm) and extreme ultra-violet (EUV) radiation (e.g. having a wavelength in the range 5-20 nm), as well as particle beams, such as ion beams or electron beams.

[0016] Embodiments of the invention will now be described, by way of example only, with reference to the accompanying schematic drawings in which:

Figure 1 depicts a lithographic projection apparatus according to a first embodiment of the invention;
Figure 2 depicts the projection system of the apparatus of Figure 1 in greater detail, showing three reflectors mounted to a frame;
Figure 3 depicts an optical element mounted via a sub- frame and two one-degree of freedom reaction masses to a projection system frame;
Figure 4 depicts an optical element mounted via two 1-degree of freedom reaction masses to a projection system frame, without a sub-frame;
Figure 5 depicts an optical element mounted via a sub frame and a single two-degree of freedom reaction mass to a projection system frame;
Figure 6 depicts two optical elements mounted via a common frame acting as reaction mass to a projection system frame;
Figure 7 depicts an optical element with an active controlled surface mounted via a sub-frame and two one-degree of freedom reaction masses to a projection system frame;
Figure 8 depicts a mount, for mounting a projection system element on the projection system frame, used in a second embodiment of the present invention;
Figure 9 depicts a variation of the mount shown in Figure 3.

[0017] In the Figures, corresponding reference symbols indicate corresponding parts.

Embodiment 1

[0018] Figure 1 schematically depicts a lithographic projection apparatus according to a particular embodiment of the invention. The apparatus comprises:

a radiation system Ex, IL, for supplying a projection beam PB of radiation (*e.g.* EUV radiation), which in this particular case also comprises a radiation source LA;
a first object table (mask table) MT provided with a mask holder for holding a mask MA (*e.g.* a reticle), and connected to first positioning means PM for accurately positioning the mask with respect to item PL;
a second object table (substrate table) WT provided with a substrate holder for holding a substrate W (*e.g.* a resist-coated silicon wafer), and connected to second positioning means PW for accurately positioning the substrate with respect to item PL;
a projection system ("lens") PL (*e.g.* a mirror group) for imaging an irradiated portion of the mask MA onto a target portion C (*e.g.* comprising one or more

dies) of the substrate W.

As here depicted, the apparatus is of a reflective type (*i.e.* has a reflective mask). However, in general, it may also be of a transmissive type, for example (with a transmissive mask). Alternatively, the apparatus may employ another kind of patterning means, such as a programmable mirror array of a type as referred to above.

[0019] The source LA *(e.g.* an discharge or laser-produced plasma source) produces a beam of radiation. This beam is fed into an illumination system (illuminator) IL, either directly or after having traversed conditioning means, such as a beam expander Ex, for example. The illuminator IL may comprise adjusting means AM for setting the outer and/or inner radial extent (commonly referred to as σ-outer and σ-inner, respectively) of the intensity distribution in the beam. In addition, it will generally comprise various other components, such as an integrator IN and a condenser CO. In this way, the beam PB impinging on the mask MA has a desired uniformity and intensity distribution in its cross-section.

[0020] It should be noted with regard to Figure 1 that the source LA may be within the housing of the lithographic projection apparatus (as is often the case when the source LA is a mercury lamp, for example), but that it may also be remote from the lithographic projection apparatus, the radiation beam which it produces being led into the apparatus (*e.g.* with the aid of suitable directing mirrors); this latter scenario is often the case when the source LA is an excimer laser. The current invention and Claims encompass both of these scenarios.

[0021] The beam PB subsequently intercepts the mask MA, which is held on a mask table MT. Having been selectively reflected by the mask MA, the beam PB passes through the lens PL, which focuses the beam PB onto a target portion C of the substrate W. With the aid of the second positioning means (and interferometric measuring means IF), the substrate table WT can be moved accurately, *e.g.* so as to position different target portions C in the path of the beam PB. Similarly, the first positioning means can be used to accurately position the mask MA with respect to the path of the beam PB, *e.g.* after mechanical retrieval of the mask MA from a mask library, or during a scan. In general, movement of the object tables MT, WT will be realized with the aid of a long-stroke module (course positioning) and a short-stroke module (fine positioning), which are not explicitly depicted in Figure 1. However, in the case of a wafer stepper (as opposed to a step-and-scan apparatus) the mask table MT may just be connected to a short stroke actuator, or may be fixed.

[0022] The depicted apparatus can be used in two different modes:

1. In step mode, the mask table MT is kept essentially stationary, and an entire mask image is projected in one go (*i.e.* a single "flash") onto a target portion C. The substrate table WT is then shifted in the x and/or y directions so that a different target portion C can be irradiated by the beam PB;
2. In scan mode, essentially the same scenario applies, except that a given target portion C is not exposed in a single "flash". Instead, the mask table MT is movable in a given direction (the so-called "scan direction", *e.g.* the y direction) with a speed v, so that the projection beam PB is caused to scan over a mask image; concurrently, the substrate table WT is simultaneously moved in the same or opposite direction at a speed $V = Mv$, in which Mis the magnification of the lens PL (typically, $M = 1/4$ or 1/5). In this manner, a relatively large target portion C can be exposed, without having to compromise on resolution.

[0023] The projection system is shown, by way of example, in Figure 2 as three reflective optical elements mounted in an optical system frame. In an apparatus, the projection system may comprise more, *e.g.* four or six, reflectors each mounted in the manner shown in Figure 2. The optical elements (in this case reflectors) M1, M2, M3 are mounted to a frame 17 via respective positioning systems that are preferably capable of positioning the mirrors accurately in six degrees of freedom. For a sub-nanometer position accuracy the position loops that control each optical element must have a high servo bandwidth, which is physically limited by the mechanical eigenfrequencies seen in the servo loop. The optical element itself is relatively compact and has relatively simple mechanics, so the dynamics can be designed with high internal mechanical eigenfrequencies (*e.g.* > 1000 Hz). The optical system frame 17, however, may contain several optical elements, is usually large and thus cannot have high internal mechanical eigenfrequencies (« 1000 Hz).

[0024] An actuator 15 drives the optical element 10 and excites the internal dynamics of it. A corresponding reaction (control) force directly put on the optical system frame 17 and/or sub-frame 11 would excite the internal dynamics of the optical sub frame 11 and of the optical system frame 17. Because the position of the element measured by servo 13 is the position of the optical element with respect to the optical system (sub) frame, this position measurement includes the dynamics of the optical element 10 and the dynamics of the optical sub frame 11 (if present) and optical system frame 17. The dynamics of the optical system frame (symbolically shown by connection 18)will form a severe limit on the achievable servo-bandwidth and thus on the positioning accuracy of the mirror.

[0025] According to the invention, the difficult dynamics of the optical frame can be removed from the servo loop by introducing a reaction mass 14 between the reaction (control) force and the optical sub frame 11 (as shown in Figure 3) or the optical system frame 17 (as shown in Figure 4). With this arrangement, the eigenfrequency (typical 5-20 Hz) of the reaction mass 14 (and

compliance 16) forms a mechanical low-pass filter for the transmission of reaction force to the optical system frame. Reaction forces with frequencies below the reaction mass eigenfrequency are transmitted directly to the optical system frame. But all reaction forces above this frequency become low pass filtered (roll off = -40 dB/decade) and excite the optical system dynamics. The effect on control stability is that the servo loop does not contain the dynamics of the optical system frame and sub-frame. The servo loop then can have a very high bandwidth because it only contains the high frequency dynamics of the optical element and some small effects of the low frequency dynamics of the reaction mass (typical at ca. 10 Hz) that do not form a problem for control stability. So a high servo bandwidth and thus positioning accuracy is possible, despite the low frequency dynamics of the optical system frame.

[0026] Two alternative arrangements for mounting optical elements are shown in greater detail in Figures 3 and 4.

[0027] Figure 3 depicts a mount for a projection system element 10 such as a mirror to fix it to a projection system frame 11 within the projection system PL via a sub-frame 11. The schematic system shown is capable of adjusting the position of the mirror in two degrees of freedom: linear displacement in a first direction (vertical as shown in Figure 2) and rotational displacement about a second direction (perpendicular to the plane of Figure 2), giving two degrees of freedom. More degrees of freedom will generally be required - up to six degrees of freedom (three translational and three rotational) for each mirror. Further the projection system will comprise several projection elements. Those degrees of freedom not shown in Figure 2 may be reached in a corresponding manner with the appropriate modifications.

[0028] The projection system element 10 may be supported by gravity compensators 12 which may, for example, be mechanical springs as depicted in Figure 3 or may be based on pneumatic principles, permanent magnets or other suitable means. The purpose of the gravity compensators is to support the projection system element against gravity, reducing the force to be exerted by the actuators 15 used to position the projection system element 10 and therefore their power dissipation. If the cooling of the vertical motors is sufficiently good, an additional gravity compensator is not required and gravity force can be compensated by motor force. The positioning actuators 15 are, preferably, Lorenz-force motors. The actuators 15 operate against reaction masses 14 which are compliantly mounted to the projection system frame 11 with a spring 16 (or alternative resilient means) that has a low suspension frequency. Preferably the resonant frequency of the suspension of the reaction mass will generally be in the range 0 to 100 Hz, for instance, of the order of 10 Hz. Such a mount may be referred to as a soft mount. The reaction mass includes the magnet or, preferably, the motor coil of the Lorenz-force motor so that the heat source is away from the optical element. Further background on Lorenz-force motors and gravity compensation is, for instance, disclosed in EP 1,001,512 A, incorporated herein by reference.

[0029] Position sensors 13 are used to measure the position of the projection system element 10 relative to the sub-frame 11 or directly to the projection system frame 17. Depending on the requirements of the control system the position sensors may be used to determine the relative displacement, velocity and accelerations of the projection system element.

[0030] In general the forces needed to position the optical element 10 are small, because the motion of the (vibration isolated) projection system frame 17 is small. Excitations of the projection system frame 17 by the reaction motor control force itself, however can create a severe stability problem for the closed loop controlled optical element. The application of a reaction mass 14 prevents the reaction force of-the Lorenz-force motors 15 from disturbing the sub-frame 11 mounted on the projection system frame 17. In an alternative construction shown in Figure 4, the sub-frame 11 is omitted and the compliance 16, gravity compensators 12 and sensors 13 are mounted on the projection system frame 17.

[0031] In effect the compliant mounting 16 of the reaction mass 14 to the projection system frame filters the reaction force of the Lorenz motor for frequencies above the eigenfrequency of the reaction mass. This eigenfrequency is determined by the mass of the reaction mass 14 and the stiffness of the soft mount 16. The reaction force filtering in turn reduces the amount of positional noise in the sub-frame 11 that could be transmitted to the respective element 10 itself and to the other projection system elements attached to the projection system frame 17. Effectively the internal projection system dynamics becomes invisible to the position control loop of the projection system elements. The result is that the control stability of the control system for the projection system elements is much improved, especially at higher frequencies, (*i.e.* there is a greatly reduced return path for actuator reaction forces to the projection system frame forming the reference for the position measurement). A control loop can therefore be designed with a very high positional bandwidth in the range 100 to 1000 Hz, for example approximately 300 Hz. This in turn means that the positional accuracy is greatly increased. The projection system element may therefore be positioned to an accuracy below approximately 0.1 nm. The internal dynamics of the projection system are therefore not affected when actuating the projection system elements. Above the eigenfrequency of the softly mounted reaction mass, the projection system element(s) cannot excite the projection system dynamics; its "dynamic mass" is not felt by the projection system.

[0032] The control of the projection system element is preferably effected by one or more control loops which may include and possibly combine both velocity and positional loops.

[0033] In the case of a projection system element being positioned in the manner described above in more than one degree of freedom, the reaction masses used with each actuator may be independent (as shown in Figures 3 and 4) or may be connected to form one or more combined reaction masses 14a, as shown in Figure 5. Furthermore, the reaction masses of several or all optical elements can be combined into one body 14b, as shown in Figure 6. The single body can then either be mounted on the projection optics frame 17 or on the base frame BP.

[0034] The projection system frame 11 shown in Figure 2 may be a frame that is common to all optical elements within the projection system, but may also be a sub-frame to which one or more optical elements are mounted, said sub-frame being mounted in some manner to the common frame of the projection system. Because of the reaction masses, the position loop of one optical element is not disturbed by the reaction forces of a position control loop of another optical element. Generally the common frame of the projection system may be mounted on a frame of the lithographic apparatus. which is vibrationally isolated with respect to a base frame of the apparatus so as to constitute an isolated reference frame. The projection optics frame may be mounted to the reference frame compliantly, as described in European Patent Application number 02254863.0.

[0035] Figure 2 shows gravity compensators 12 mounted between optical element 10 and frame 11. In an alternative embodiment such gravity compensators 12 may be mounted between reaction mass 14 and optical element 10 although this is less efficient. However, the gravity compensators might also be dispensed with. Actuators that do not act in the vertical direction will not experience a gravity force by the optical element 10 and do not require a gravity compensator at all. Any gravity compensation force should be arranged to act in line with the vertical control force to minimize bending moments that may result in a deformation of the optical surface.

[0036] An ideal one-degree of freedom reaction mass has a soft stiffness exactly in line with the direction of the reaction force (typically 2-20 Hz). A misalignment may result in an undesirable excitation of the optical system frame. The reaction mass can be made less sensitive for a misalignment of reaction forces if the other degree of freedoms are fitted with a "medium soft" suspension eigenfrequency. Usually this "medium stiffness" is 5 to 10 times higher as in the "soft" direction (typically 10-50 Hz).

[0037] In yet another variant of the first embodiment the reaction mass 14 is not softly mounted to the frame of the projection system, but to another frame of the lithographic apparatus, for instance base frame BP or the isolated reference frame onto which the common frame of the projection system is mounted.

[0038] A further variant of the first embodiment is shown in Figure 7. This variant incorporates an active mirror surface that can adjust for mirror surface imperfections. A thin and light (*e.g.* of mass 0.1 kg) reflective mirror surface 21 is placed on top of a thick support mirror structure 10 (*e.g.* of mass 1 to 10 or 30 kg), with multiple (*e.g.* from 9 to 64) small actuators 22, multiple sensors 24 and possibly multiple additional structural supports 23 in between. The structural supports 23 may comprise an array of burls.

[0039] The multiple actuators have very small stroke (<10e-6 m) and control the relative position of the mirror surface with respect to the mirror structure. The actuators could be of pneumatic, piezo-, electro-static, magneto-restrictive type. Using multiple actuators enables a local deformation of the surface and thus to correct for local mirror surface imperfections. The large six-degree of freedom rigid body position (*ca.* 10-1000e-6 m) is controlled with the Lorenz motors with reaction mass as is described above.

[0040] Because the total mass of the multiple surface actuators and flexible mirror is relatively small when compared to the mirror structure mass, the dynamics of the combination of the active surface and mirror structure can be designed to have high enough eigenfrequencies to enable both a global six-degree of freedom and a local surface sub-nanometer optical positioning with high servo bandwidth (*e.g.* 250-400 Hz). For a less accurate system, the 6 DOF Lorenz motors with reaction mass(es) may be replaced by other type of actuator or flexures.

[0041] The active mirror surface with multiple actuators enables a real time correction of the local mirror imperfections, resulting in less smeared and deformed images at wafer level.

Embodiment 2

[0042] A second embodiment of the present invention is similar to the first embodiment but differs in the arrangement of the mounts for the projection system elements, which are depicted in Figure 8. In this case the reaction mass 54 is used to "absorb" vibrations of the projection system element 50. The projection system element 50 is mounted on part of the projection system, such as the projection system frame 51, by means of actuators 52 (such as Lorenz-force motors, piezo-electric actuators, magnetorestrictive actuators, etc.) and, preferably, gravity compensators 53. A reaction mass 54 is attached to the projection system element 50 by means of actuators 55 but is not directly mechanically attached to the projection system (if, however, the reaction mass is the coil of an actuator, it may have connections directly to the projection system for utilities, such as power and cooling).

[0043] By controlling the actuators 55 appropriately, any undesired vibrations of the projection system element may be attenuated. In order to detect vibrations of the projection system element, a second mass 56 is at-

tached to the projection system element 50 by means of a sensor 57, such as a piezo-sensor or magneto-restrictive sensor for example, to form an accelerometer. The use of two sensors 57 and two actuators 55, as shown in Figure 8, allows the measurement and attenuation of vibrations in both a linear first direction (vertically as shown in Figure 8) and rotationally about a second direction, perpendicular to the first (about an axis perpendicular to the plane of Figure 8).

[0044] It should be appreciated that the above arrangement can be applied to damp vibrations in both compliantly mounted optical elements and stiffly mounted, e.g. with an eigenfrequency of 400Hz or more, optical elements.

[0045] Figure 9 shows an alternative arrangement of the projection system element mount shown in Figure 8. As before, the projection system element 60 is mounted on the projection system frame 61, for example, by means of actuators 62 and gravity compensators 63. A reaction mass 64 is attached to the projection system element to attenuate unwanted vibrations. In this case, the sensor 67 and the actuator 65 are stacked and use a common mass 64. In this arrangement the actuator 65 is preferably a piezo-actuator and the sensor 67 is preferably a piezo-sensor. The sensor 67, located between the reaction mass 64 and the actuator 65, detects the vibration of the projection system element 60. The actuator 65 is then used to correct the movement of the projection system element to reduce the unwanted vibration. As in the arrangement shown in Figure 8, a pair of sensors and actuators could be used to attenuate rotational vibrations as well as linear vibrations.

[0046] Although not shown in either Figure 8 or Figure 9, the vibrations of the projection system element will typically need to be controlled in six degrees of freedom. Appropriately modified combinations of reaction masses, sensors and actuators can be used to effect control of the degrees of freedom not shown. Where appropriate the reaction masses used and/or the masses used for the sensors may be combined to form one or more combined masses.

[0047] Although for simplicity it is not shown in any of the Figures, the first and second embodiments may be combined to both reduce the vibrations transferred between the projection system frame and the projection system elements (using the arrangement shown in Figure 3 or 4) and to attenuate any vibrations that do exist in the projection system element (using the arrangement shown in Figures 8 and 9).

[0048] Further, the projection system elements 10, 50, 60 are quite generally shown in the Figures. They may comprise refractive and reflective optical elements but also other types such as diffractive elements.

[0049] Whilst specific embodiments of the invention have been described above, it will be appreciated that the invention may be practiced otherwise than as described. The description is not intended to limit the invention.

Claims

1. A lithographic projection apparatus comprising:

   - a radiation system for providing a projection beam of radiation;
   - a support structure for supporting patterning means, the patterning means serving to pattern the projection beam according to a desired pattern;
   - a substrate table for holding a substrate;
   - a projection system for projecting the patterned beam onto a target portion of the substrate,

   characterized in that at least one of said projection and radiation systems comprises at least one optical element connected by an actuator to a reaction mass that is moveable in at least one degree of freedom, the force exerted by the actuator between the reaction mass and the optical element being used to control the position of the optical element in one or more degrees of freedom.

2. A lithographic projection apparatus according to claim 1, further comprising a resilient member connecting the reaction mass to a frame of the apparatus.

3. A lithographic projection apparatus according to claim 2, wherein said frame is a frame of the projection system.

4. A lithographic projection apparatus according to claim 2 wherein said frame is part of a base frame of said apparatus.

5. A lithographic projection apparatus according to claim 1, 2, 3 or 4, further comprising a sensing means for determining the position of the optical element and wherein said actuator is responsive to said sensing means such that the optical element is adjusted to be in a required position.

6. A lithographic projection apparatus according to any one of claims 1 to 5, wherein said optical element is connected to a plurality of actuators each of which is connected to a respective reaction mass.

7. A lithographic projection apparatus according to any one of claims 1 to 5, wherein said optical element is connected to a plurality of actuators for exerting forces in different directions connected to a single reaction mass that is moveable in corresponding directions.

8. A lithographic projection apparatus according to any one of claims 1 to 5 comprising a plurality of optical elements, each with one or more actuators,

actuators of plurality of optical elements being connected to a single reaction mass.

9. A lithographic projection apparatus according to any one of the preceding claims wherein said optical element has an active controlled optical surface, said active optical surface having multiple local position control loops formed by multiple sensors and actuators that can correct for local reflective mirror imperfections.

10. A lithographic projection apparatus according to claim 1, wherein the reaction mass is mechanically connected only to the optical element.

11. A lithographic projection apparatus according to claim 10, further comprising a sensing means for detecting the motion of the optical element and wherein said actuator is responsive to said sensing means to adjust the position of the optical element such that the motion of the optical element is reduced.

12. A lithographic projection apparatus according to any one of claims 2 to 9, wherein the projection system further comprises:

- a second reaction mass connected to said optical element by a second actuator; and
- the reaction of the force exerted by the second actuator between the second reaction mass and the optical element is used to adjust the position of the optical element; and

wherein the second reaction mass is mechanically connected only to the optical element.

13. A lithographic projection apparatus according to claim 12, further comprising a second sensing means for detecting the motion of the optical element and wherein said actuator is responsive to said sensing means to adjust the position of the optical element such that the motion of the optical element is reduced.

14. A lithographic projection apparatus according to any one of the preceding claims, wherein said actuator is a Lorenz-force motor.

15. A lithographic projection apparatus according to any one of claims 1 to 13, wherein the actuator is a piezo-actuator.

16. A device manufacturing method comprising the steps of:

- providing a substrate that is at least partially covered by a layer of radiation-sensitive material;
- providing a projection beam of radiation using a radiation system;
- using patterning means to endow the projection beam with a pattern in its cross-section;
- projecting the patterned beam of radiation onto a target portion of the layer of radiation-sensitive material using a projection system,

characterized in that:

- an actuator is connected between a reaction mass that is moveable in at least one degree of freedom and an optical element in at least one of the projection and radiation systems; and by the step of
- using the force exerted by the actuator between the reaction mass and the optical element to control the position of the optical element.

Fig. 1

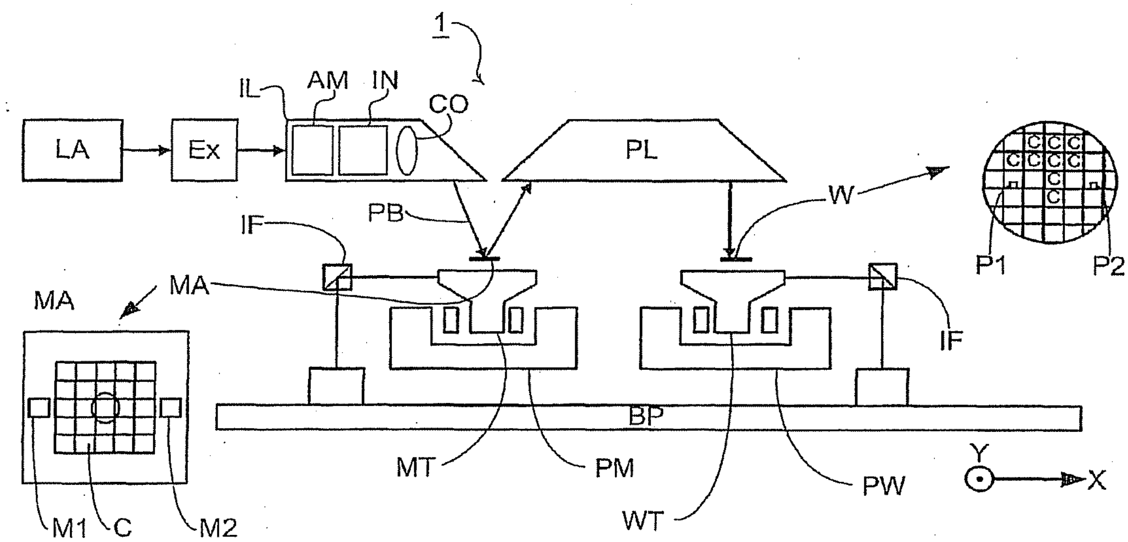
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Fig. 2

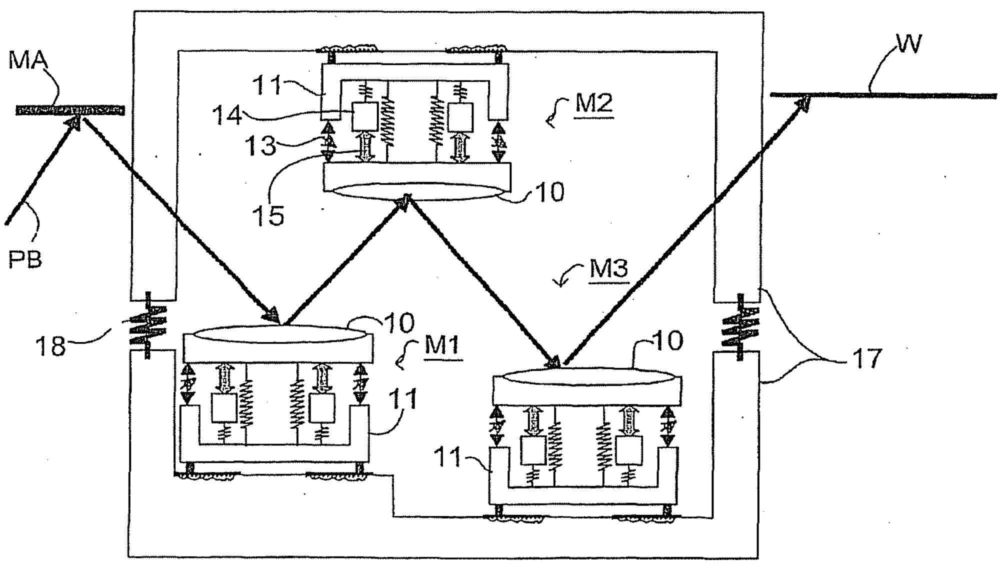
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Fig. 3

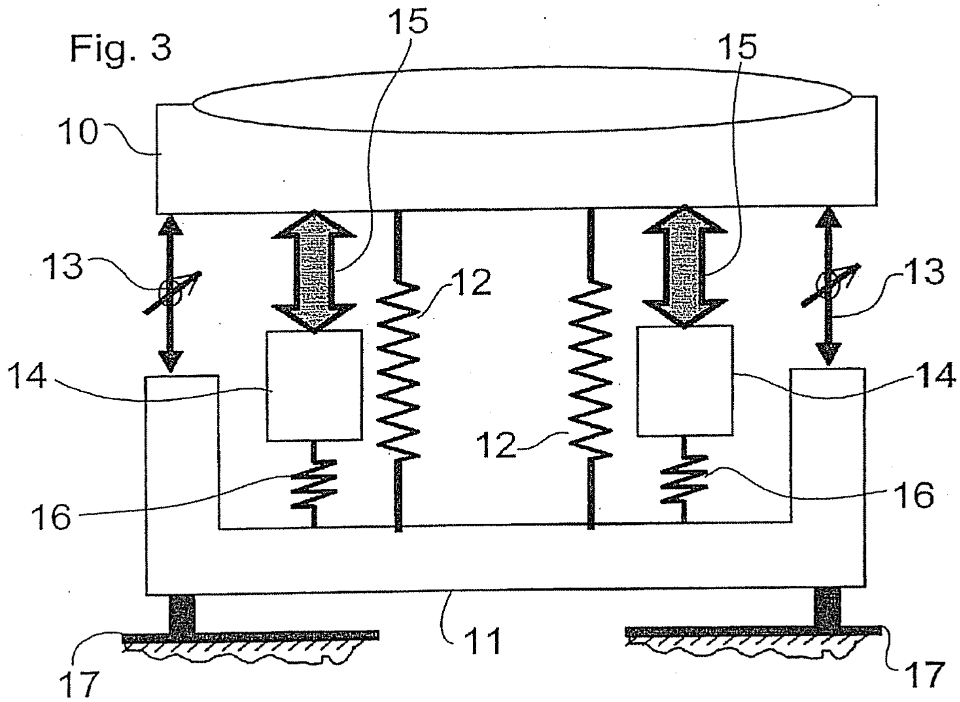
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Fig. 4

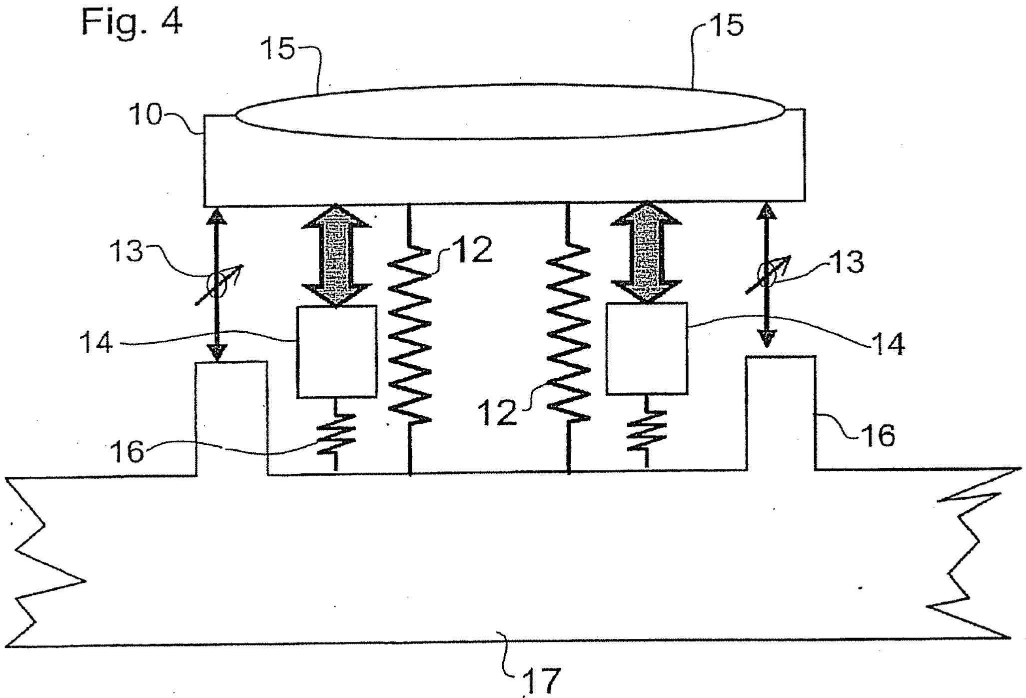
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Fig. 5

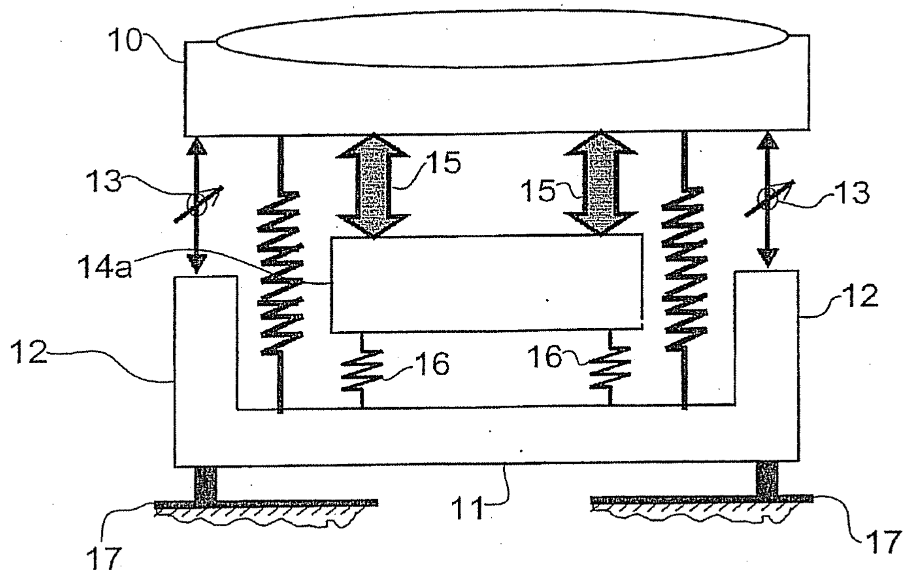

Fig. 6

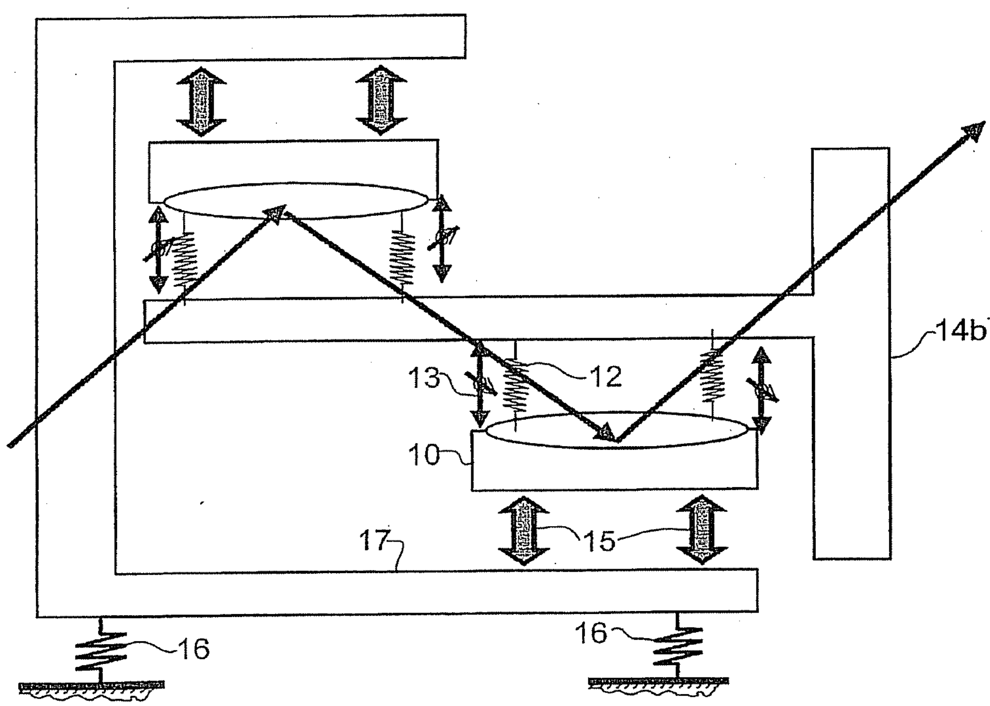

Fig. 7

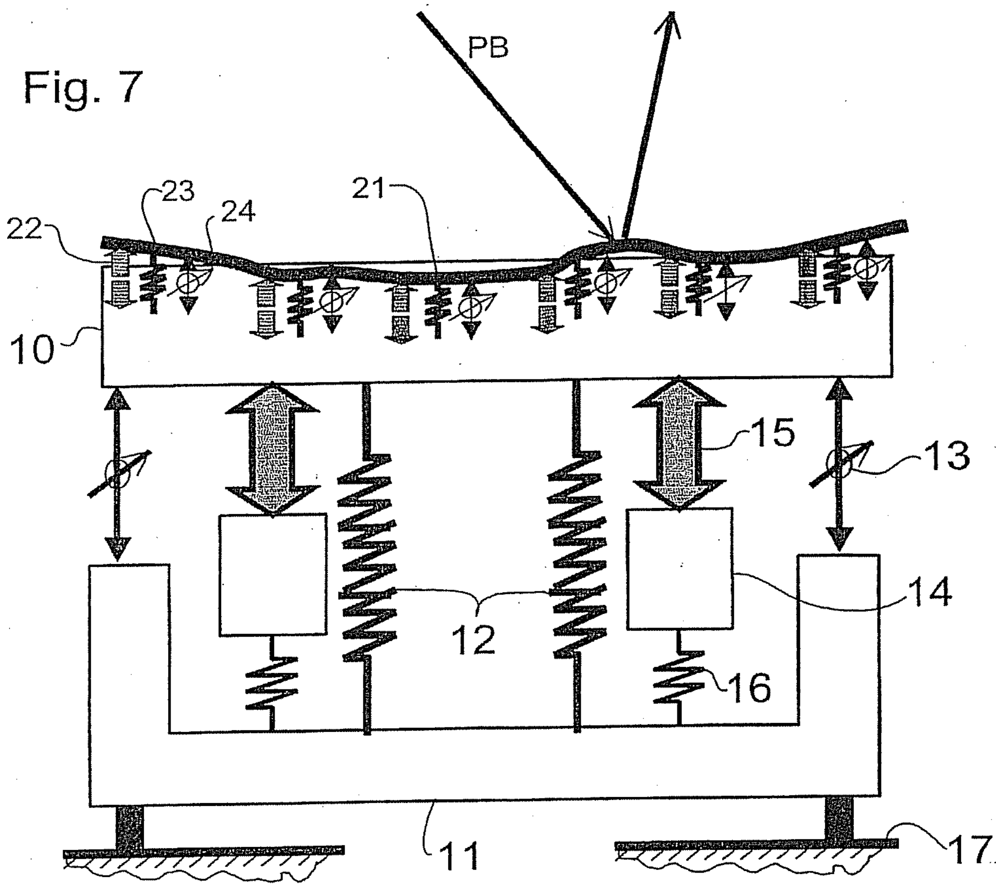

Fig. 8

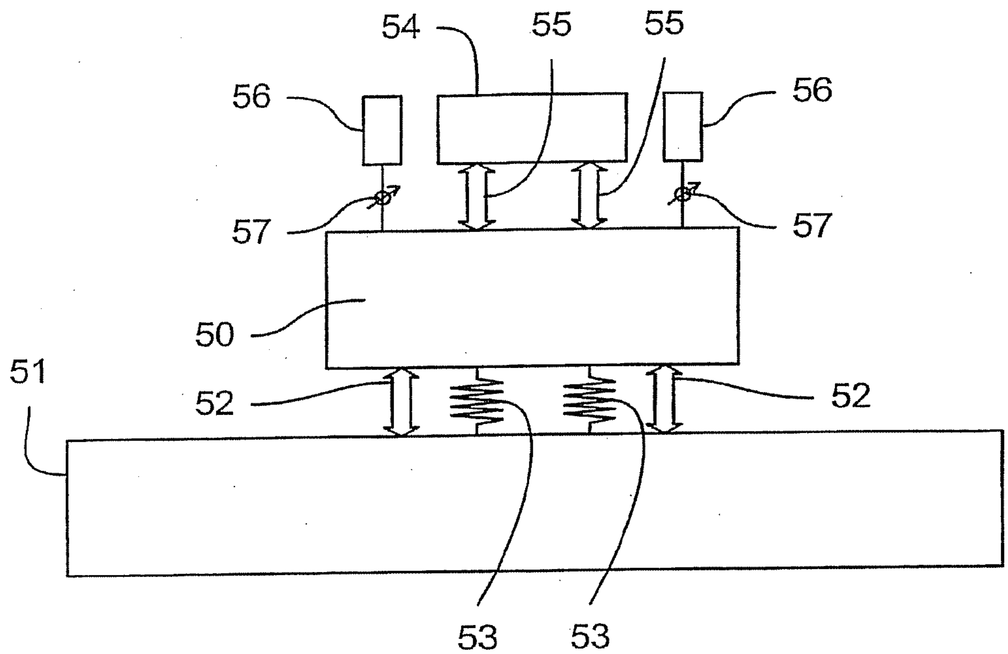

Fig. 9